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SLEEVE BEARING MATERIALS AND LUBRICANTS FOR ADVANCED AIRFRAMES

Keith F. Dufrane, et al

Battelle Columbus Laboratories

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SUMMARY REPORT

on

SLEEVE BEARING MATERIALS AND LUBRICANTS FOR ADVANCED AIRFRAMES

to

NAVAL AIR SYSTEMS COMMAND
DEPARTMENT OF THE NAVY

January 29, 1973

Prepared Under Contract N-00019-72-C-0178

by

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13. ABSTRACT

An evaluation of improved materials for bearings, shafts, and lubricants for airframe-bearing applications has been made using a laboratory apparatus which simulates the operating conditions encountered in actual aircraft. Hardened 440C stainless steel shafts were found to have excellent compatibility with beryllium-copper bearings at high bearing stress levels. Therefore, this steel holds considerable promise for use as a high-performance, corrosion-resistant shaft material. Hardened 300-M shafts were subject to fatigue cracking at bearing stresses above 40,000 psi (the fatigue cracking was similar to that experienced with AISI 4340). Shot peening prior to plating and baking after plating was found to increase the fatigue resistance sufficiently to permit operation at 60,000 psi. Three greases meeting the MIL-G-81322 specification performed well at temperatures to 350 F, and additions of either $AsSbS_4$ or MoS_2 were found to enhance the grease performance even further.

Details of illustrations in this document may be better studied on microfiche

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SLEEVE BEARING MATERIALS AND LUBRICANTS
FOR ADVANCED AIRFRAMES

by

K. F. Dufrane, F. F. Zugaro, and W. A. Glaeser

INTRODUCTION

As the performance requirements of advanced aircraft increase, there is a corresponding need for improved plain-bearing materials and lubricants to meet the more rigorous operating requirements. In the past several years, Battelle's Columbus Laboratories (BCL) has conducted research programs to identify new bearing and shaft materials and lubricants and to develop the design data needed to apply them. Design charts and recommendations relating bearing load capacity, wear, and cycles of operation were developed experimentally using a laboratory apparatus to simulate the operation and environment of actual airframe bearings.

The earlier research programs were conducted under Contracts NOas-54-344C, NOw-60-049-6, and NOw-62-0432-C. Design recommendations based on this work were incorporated in MIL-HDBK-5, Paragraph 8.2.3.1, "Joints Having Motion - Plain Bearings". More recent research was conducted under Contracts N-00019-69-C-0293, N-00019-70-C-0282, and N-00019-71-C-0119. In addition to the development of design data for new materials and lubricants, these programs were directed toward understanding the lubrication process to permit the identification of optimum lubricant-bearing systems having long-life and fail-safe features. The current 13-month program, summarized in this report, is a continuation of these studies.

SUMMARY

Shafts of hardened 440C stainless steel were found to have exceptional compatibility with beryllium-copper bearings at room ambient temperatures. The shaft contact surfaces were highly polished and the bearing wear rates were low. The performance was inconsistent at elevated temperatures; some of the shafts showed evidence of transfer of the bearing material. However, in all cases the wear was satisfactory. Thus, the wear performance of 440C combined with its inherent corrosion resistance suggests its consideration for an airframe shaft material.

Hardened 300-M steel shafts showed a performance comparable to AISI 4340 shafts. Both shaft materials were subject to failure by fatigue when chrome plated and run at stresses higher than 40,000 psi. Shot peening the shafts prior to plating and baking immediately after plating were found to eliminate the fatigue problem. The procedure also appeared to enhance the adhesion of chrome, since both types of shafts were run successfully for extended times at a 60,000 psi bearing stress.

All greases meeting the MIL-G-81322 specification performed well at operating temperatures to 350 F. Greases studied in previous programs produced degraded bearing performance at temperatures above 300 F, which suggests that formulation changes have been made that result in enhanced high-temperature operation.

The addition of either $AsSbS_4$ (ATA) or MoS_2 to MIL-G-81322 grease resulted in improved performance of aluminum-bronze bearings. The coefficient of friction was reduced and operation at higher stresses was possible.

CONCLUSIONS

The following conclusions have been reached from this study concerning airframe-bearing operation and design.

(1) Shafts of hardened 440C stainless steel show excellent compatibility with beryllium-copper bearings lubricated with MIL-G-81322 grease at ambient temperatures.

(2) The performance of 440C stainless steel shafts at elevated temperatures is inconsistent, but all of the wear results were low enough to permit satisfactory high-temperature operation.

(3) Shafts of hardened 4340 and 300-M steel (52 and 54 R_c, respectively) when operated without chrome plating provide satisfactory performance with aluminum bronze and beryllium-copper bearings. No improvement in performance was noted for 300-M that could be correlated with its slightly higher strength and hardness.

(4) Hardened 4340 and 300-M plated with a conventional hard-chrome coating were prone to failure by fatigue when they were operated at stresses above 40,000 psi.

(5) Shot peening 4340 and 300-M shafts prior to chrome plating and baking after chrome plating (to minimize hydrogen embrittlement) increases the fatigue resistance of these materials such that operation at 60,000 psi is possible.

(6) Three greases meeting the MIL-G-81322 specification provided satisfactory lubrication of airframe bearings at temperatures to 350 F.

Apparently, formulation changes have been made since the examination of greases conforming to MIL-G-81322 in a previous program; now such greases provide adequate boundary-lubrication properties at temperatures above 300 F.

(7) Additions of either 5 percent ATA or 5 percent MoS_2 to MIL-G-81322 show promise of improving the performance of the grease in airframe-bearing applications. The additives improved the friction performance and increased the allowable operating stress for aluminum-bronze bearings.

(8) Analysis of films found on the surfaces of beryllium-copper bearings that had operated in distress consisted of metallic elements present in the grease and in the bearing material. Strangely, cobalt, which is an alloy addition in beryllium copper, did not show up in the film (or in the grease). Similar, but much thinner films were found on bearings that had operated satisfactorily. The association of thicker films with degraded operation suggests that the films might result from higher frictionally induced temperatures, and that the wear may be chemical in nature.

RECOMMENDED FUTURE WORK

The following efforts are recommended to improve the performance of airframe bearings and provide additional design data.

(1) Optimize the shot-peening and baking steps for hard-chrome plating of airframe-bearing shafts intended for use in corrosive environments. The balance between residual compressive stresses needed (a function of shot size and intensity) and the final finishing operations required should be considered.

(2) Study the performance of ATA and MoS_2 additions to MIL-G-81322 grease in more detail to determine the practical permissible increase in bearing operating conditions that might result from the use of these additives.

(3) Determine the applicability of plasma-sprayed bearing materials for new applications and repair of existing hardware. In addition to performance improvements, potential weight savings and simplicity of design should be included in the analysis. For example, if bearings can be formed by plasma-spraying a bearing alloy directly into appropriate holes in the members of the airframe, the design could be reduced in size and simplified considerably. The bearing material could be much thinner than required for conventional bearings, and the machined bores and shoulders for mounting could be eliminated. Both a weight and a cost savings could result.

(4) Study the boundary-lubrication mechanisms operative with material and lubricant

combination sed f airframe bearings. The success ou with an ion microanalyzer and an ion scattering spectrometer in an initial analysis of surface films indicates that the composition of surface films can be determined. Such analyses should ultimately permit the specification of optimum lubricant and additive compositions for various bearing and shaft material combinations.

APPARATUS

One of the two identical airframe-bearing simulation apparatuses is shown in Figure 1. A schematic view of the specimen configuration is shown in Figure 2. The test bearing is pressed into the specimen link, which serves as its housing, and the link is held between two clevises. One clevis is fixed to the base and supports the oscillating test shaft in two heavy-duty "nonskewing" needle bearings. The other clevis is attached to a double-acting hydraulic piston, which supplies the specimen loading. The load is calculated from pressure gages on the hydraulic piston, and the bearing load is adjusted and equalized in the two radial directions with relief valves.

The test shaft is coupled to the drive shaft with a rigid coupling and oscillated with a rack-and-pinion arrangement. The rack is powered with a hydraulic piston controlled by electrically actuated valves. The rack displacement and corresponding degree of oscillation of the test shaft are controlled by limit switches on either end of the piston stroke. The shaft torque (a measure of bearing friction) is detected by strain gages in a configuration sensitive to torque but insensitive to shaft bending. The torque measurements are recorded on a Sanborn strip-chart recorder, and the torque transducers are calibrated with a torque wrench prior to testing.

The specimen loading and shaft oscillation are controlled and synchronized with electrically operated hydraulic valves controlled by cam-operated microswitches. A complete cycle consists of an application of load in one direction, a 90-degree rotation of the shaft in one direction, a reversal of the load, and a 90-degree counterrotation of the shaft. Twelve cycles are completed per minute. Grease is resupplied to the bearing by an automatic grease dispenser at two-hour intervals. The entire apparatus is equipped with safety shut-off features for automatic nonattended operation. The tests are normally run up to 60,000 cycles, but are terminated earlier if excessive wear or galling occurs. Bearing wear is monitored by dimensional measurements on the disassembled bearings at intervals during the oscillating-load test and by a dial indicator on the load ram for unidirectionally loaded tests.

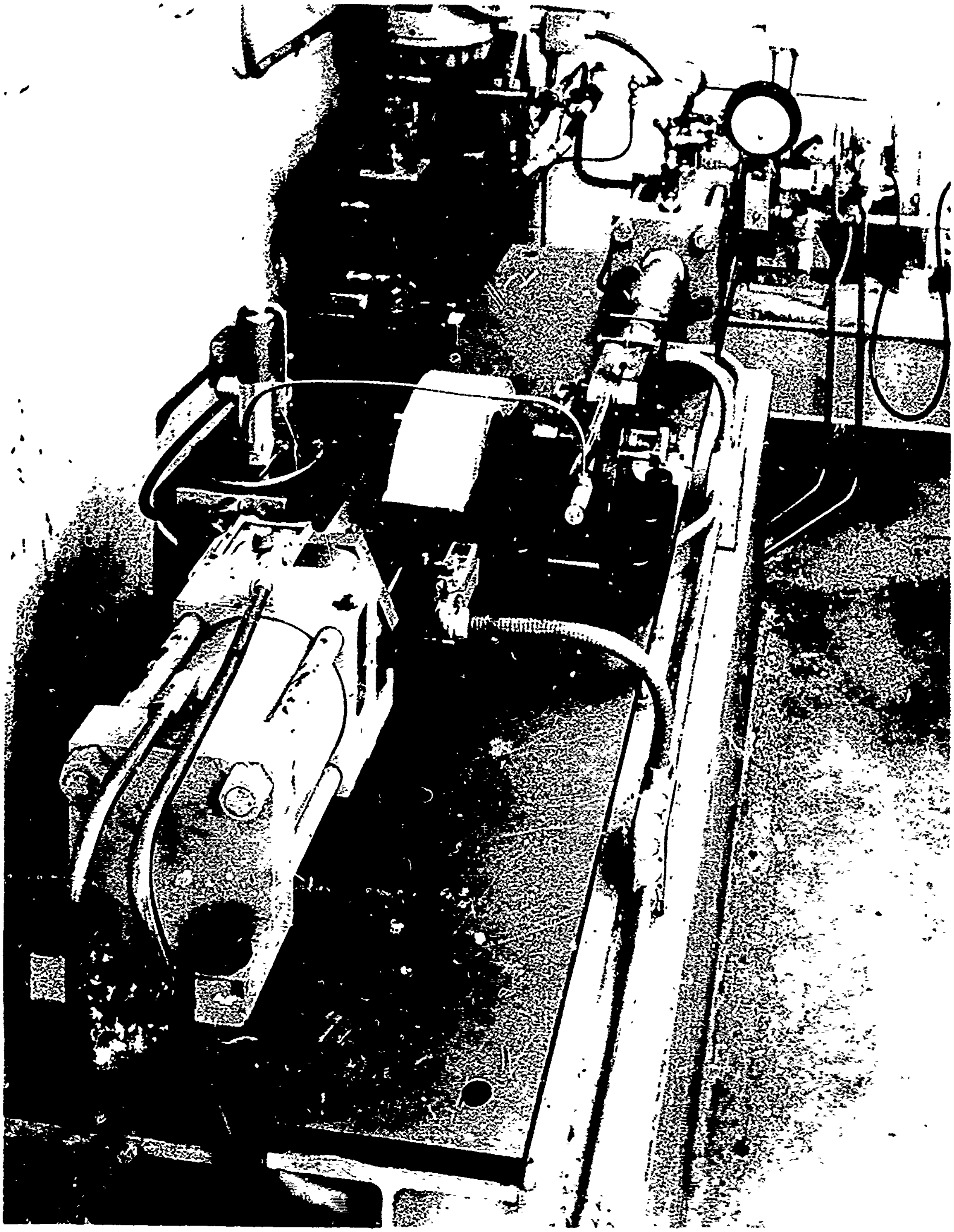


FIGURE 1. AIRFRAME BEARING SIMULATION APPARATUS

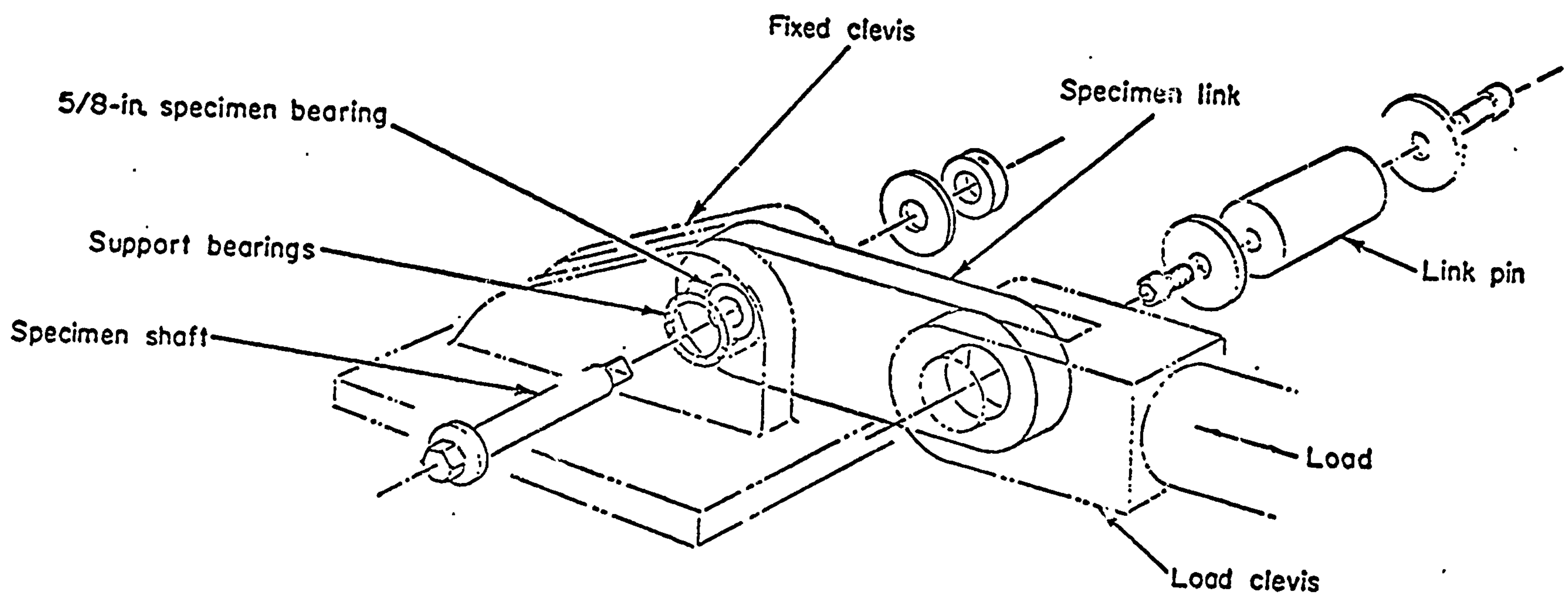


FIGURE 2. LINK AND CLEVIS CONFIGURATION FOR TEST BEARING

Elevated-temperature tests are performed with a link heated by two commercial rod heaters brazed to the top and bottom of the link (shown in Figure 1). Temperatures can be maintained at any level between room temperature and 600 F within ±2 F. The control thermocouple is welded to the link near the upper heater, and the thermocouple to monitor bearing temperature is inserted into a drilled hole in the bearing.

The operating capabilities of the apparatus (duplicate facilities are available) are summarized as follows.

- Sliding speed of bearing surface - 3-1/2 fpm
- Shaft oscillating amplitude - ±45 degrees (90 degrees total movement)
- Shaft oscillating frequency - 12 cpm
- Loading - steady state and reversing at 12 cpm
- Bearing-journal diameter - 5/8 in.
- L/D ratio - 1.0
- Bearing stress - to 90,000 psi
- Bearing temperature range - 75 to 600 F.

TEST MATERIALS

Bearings

Beryllium Copper

Beryllium copper is a very high-strength copper-base alloy, which derives its strength from a precipitation-hardening mechanism. The alloying additions that form the strengthening precipitate are 0.2 to 0.6 percent cobalt and 1.8 to 2.15 percent beryllium, depending on the alloy. Hardnesses of up to 45 R_c can be obtained in a fully heat-treated structure.

Alloy 25 was used for the bearings in the study. The material, as received, had been given an homogenizing heat treatment, hot and cold worked, and given a precipitation heat treatment to produce a homogeneous microstructure with fine grain size. The final hardness was R_c 40, and the bearings were machined directly from the bar stock without further treatment.

Cast Aluminum Bronze

The aluminum bronze obtained for the study was manufactured to MIL-B-6946 specifications. Since hardness and strength levels comparable to beryllium copper cannot be obtained with aluminum bronze, its load-carrying capacity in plain-bearing applications is generally lower.

Plasma-Sprayed Aluminum Bronze and Beryllium Copper

Experimental quantities of plasma-sprayed aluminum-bronze and beryllium-copper bearings were obtained from an industrial source for evaluation. A layer of the plasma-sprayed material approximately 0.010 inch in thickness was deposited on the inner diameter of an enlarged conventional bearing. The plasma-sprayed material had reportedly shown improved performance over conventional material in other bearing tests, which warranted its evaluation for airframe-bearing applications.

Configuration

The bearing configuration is shown in Figure 3. Grease was supplied through the grease feeder holes and central circumferential distribution groove. The bearings were rough machined from bar stock, heat treated as required, final machined on the sides and outer diameter, pressed into the links, and final finished on the inside diameter. The inside diameters were machined to match the individual test shafts with a final clearance of 0.001 to 0.002 inch. Measurements of the bearing wear were reported as total increases in the machined diameter in the loaded directions.

Shafts

The four shaft materials used for the experiments included M50 tool steel, AISI 4340 steel, 300-M steel, and 440C stainless steel. The M50 and 440C steel shafts were quenched and tempered

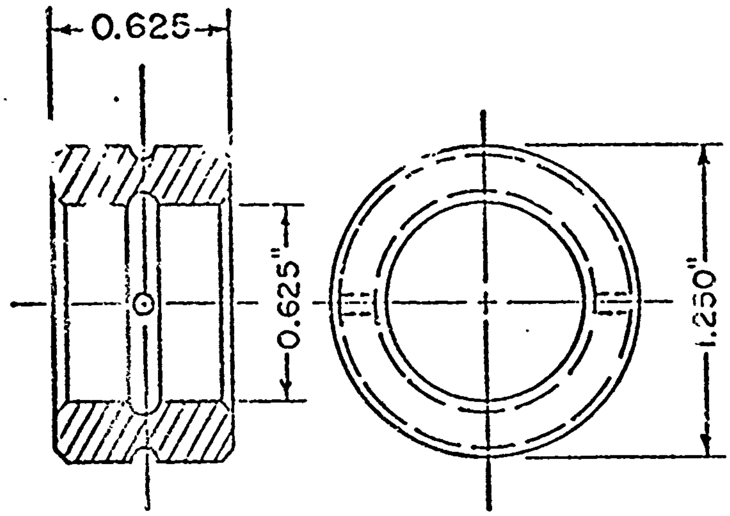


FIGURE 3. BEARING CONFIGURATION

to a hardness of 58 to 60 R_c, finish ground, and used directly without further surface treatment. The AISI 4340 shafts were quenched and tempered to a hardness of 35 R_c or 52 R_c; the 300-M shafts were quenched and tempered to a hardness of 54 R_c. The AISI 4340 and 300-M shafts were used directly after finish grinding or were plated with approximately 0.002 inch of hard chromium.

Lubricants

The lubricants used for the study included three greases meeting the MIL-G-81322 specification, and two BCL-modified versions of MIL-G-81322. The three MIL-G-81322 greases were identified as XRR 38A, 142847, and "standard" MIL-G-81322. The two BCL-modified versions consisted of a MIL-G-81322 grease containing a 5 percent additions of either MoS_2 or of $AsSbS_4$ (ATA, Pennwalt Corporation).

EXPERIMENTAL RESULTS

Bearing and Shaft Performance Studies

440C Stainless Steel Shafts

Preliminary experiments with 440C stainless steel shafts conducted under Contract N-00019-71-C-0119 showed encouraging results when used with beryllium-copper bearings. The bearing wear rates were low, and the shaft surface showed evidence of good compatibility between the mating materials. Because of the inherently better corrosion resistance of 440C stainless steel when compared with that of M50 tool steel, further experiments with 440C stainless steel shafts were conducted to determine its overall suitability.

Since the initial results were obtained at room temperature, a series of experiments were conducted to determine the elevated-temperature performance of 440C stainless steel shafts operating with beryllium-copper bearings. The results are shown in Figures 4 and 5. The two versions of MIL-G-81322 grease produced performance variations, which can be seen by comparing the two graphs. However, since none of the bearings had excessive wear rates, it can be concluded that 440C stainless steel shafts show promise for elevated-temperature service. For the XRR 38A formulation of MIL-G-81322 grease, data for which are shown in Figure 4, the bearing wear was very low at 40,000 psi stress and 300 F. In comparison, an identical experiment (performed in the previous program) with an M50 shaft resulted in similar bearing wear. Operation at a stress of 60,000 psi with 440C shafts caused a significantly higher wear rate than did that measured at lower stresses, and the wear rate was not changed by varying the operating temperature from 250 to 300 F. This result suggests that for 440C stainless steel shafts, the effectiveness of the lubricant is limited at higher stress levels and temperatures.

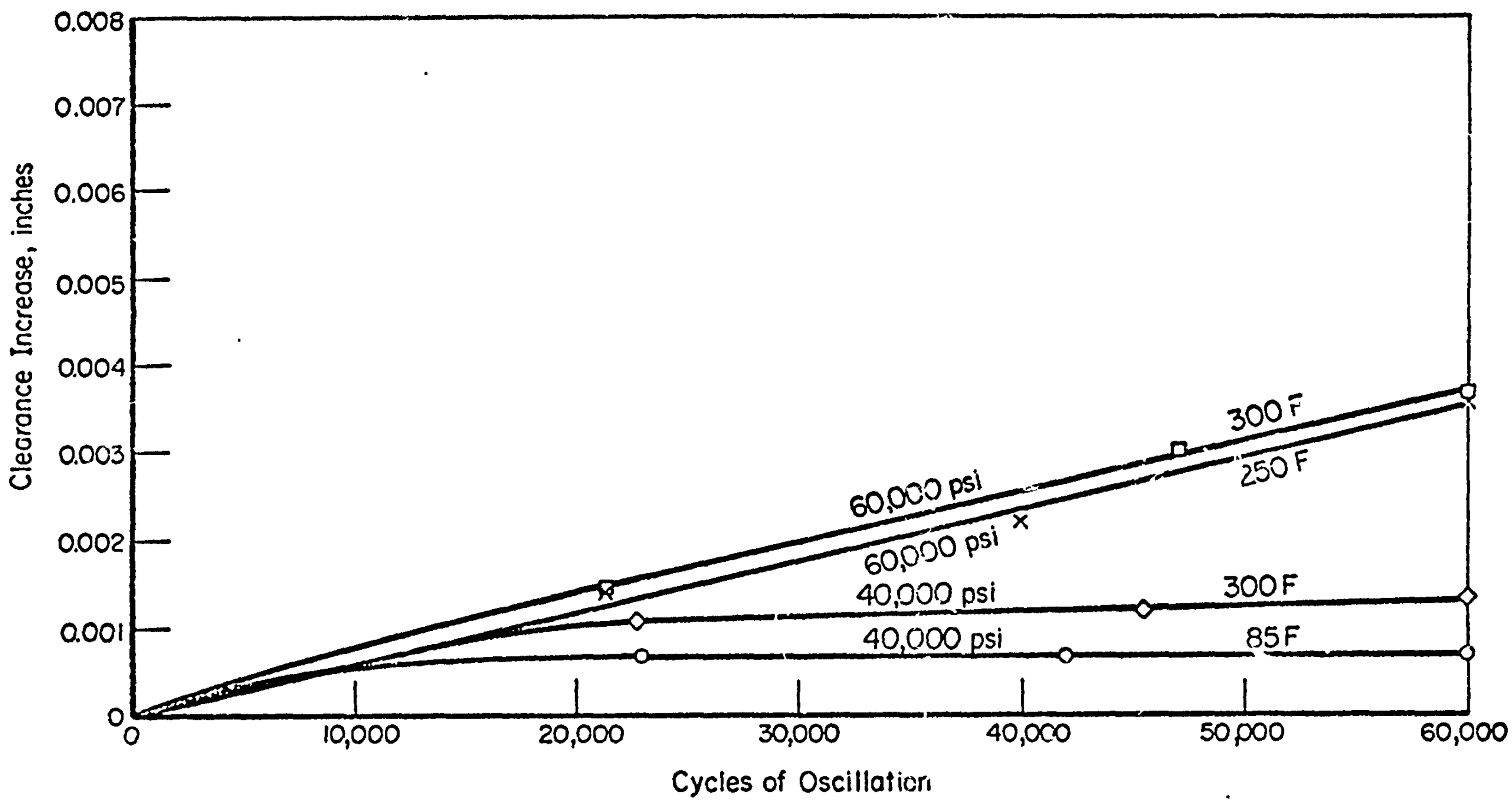


FIGURE 4. ELEVATED-TEMPERATURE PERFORMANCE OF BERYLLIUM-COPPER BEARINGS AGAINST 440C STAINLESS STEEL SHAFTS WITH THE XRR 38A FORMULATION OF MIL-G-81322 GREASE

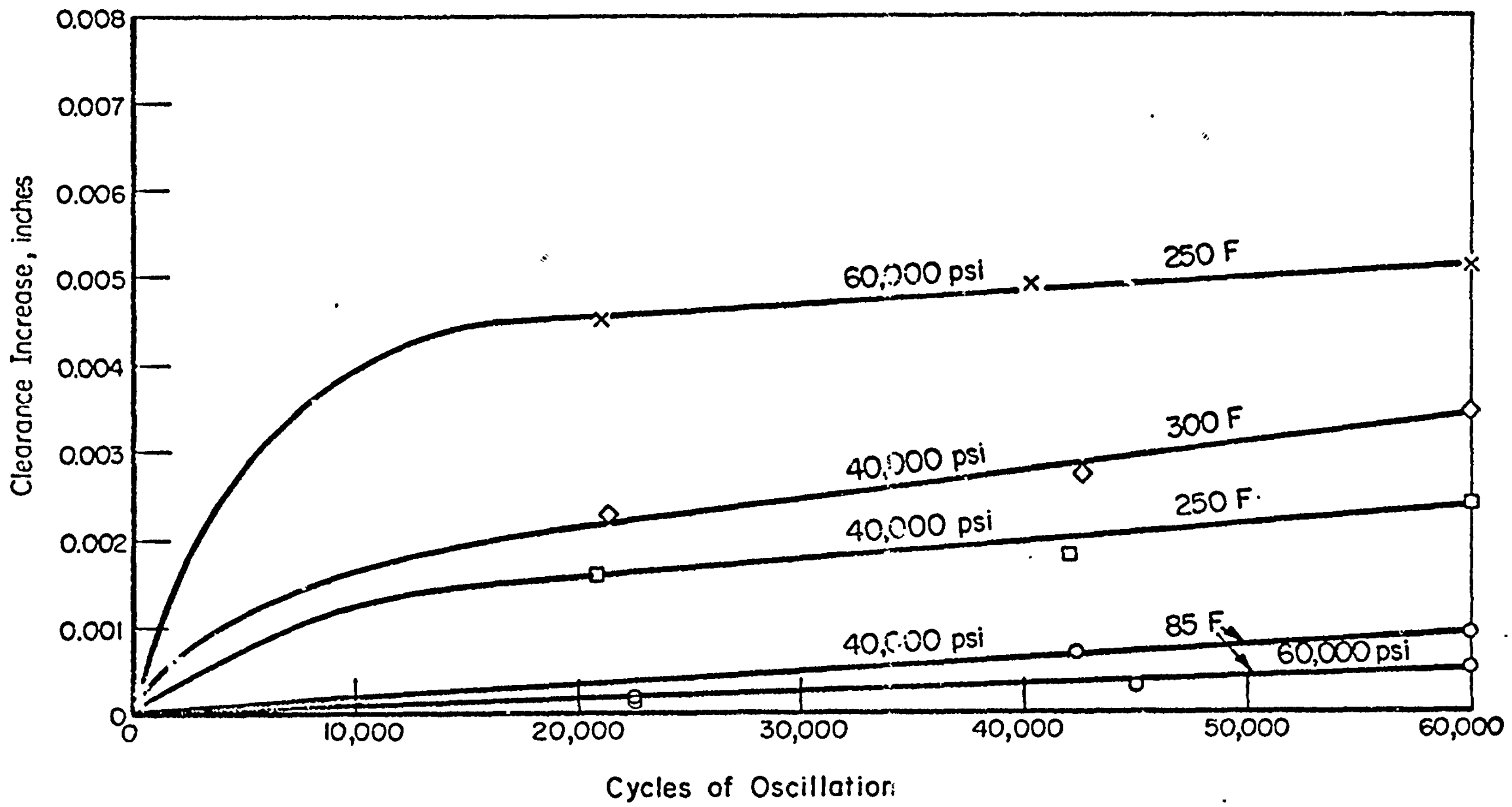


FIGURE 5. ELEVATED-TEMPERATURE PERFORMANCE OF BERYLLIUM-COPPER BEARINGS AGAINST 440C STAINLESS STEEL SHAFTS AND STANDARD MIL-G-81322 GREASE

As shown in Figure 5, the bearing wear also increased with higher stress and temperature when MIL-G-81322 grease was studied. The bearing wear was higher in all cases than was that measured for the XRR 38A formulation of MIL-G-81322. For comparison, beryllium-copper bearings operating with M50 shafts will show 0.002 inch of wear (or less) after 60,000 cycles of oscillation.

The performance of the 440C stainless steel shafts in terms of bearing wear could be associated with the appearance of the shaft surface in the contact region. All of the shafts operated at room temperature developed a highly polished contact area with no apparent transfer of copper from the bearing to the shaft. In contrast, the experiments showing higher wear rates at elevated temperatures produced darkened shaft surfaces with evidence of copper transfer from the bearing. As shown in Figures 4 and 5, the ability to attain low wear rates at elevated temperatures (with associated highly polished shaft surfaces) was not consistent. The attainment of good compatibility was evident early in the experiments. When the shafts became polished, the wear rate decreased after the initial accommodation period and remained at a low level. Evidently, the variations in performance at elevated temperatures involves complex surface interactions, especially in the initial portion of the experiment where any early material transfer may prevent subsequent surface conditioning (polishing). This was borne out by observations that any evidence of material transfered to the shafts early in the experiments invariably was associated with higher bearing wear rates during the remainder of the experiment.

Experiments were performed to evaluate the corrosion performance of 440C stainless steel shafts in contact with beryllium-copper bearings. The experiment consisted of repeated dipping into seawater of an assembled bearing and shaft. A light smear of MIL-G-81322 grease was placed on the shafts to reproduce normal bearing lubrication. The

dipping cycle consisted of 1 minute in the seawater followed by 4 minutes out of water. A fan was used to dry the specimens when out of the water, which produced a wide range of salt concentrations at the surfaces during each cycle. The corrosion evaluations were continued for 5 days, followed by 2 days of air drying, followed by an additional 5 days of dipping. The materials were evaluated by observing the extent of corrosion at the junction of the shaft and bearing. This procedure, which subjects the bearing and shaft to a severe marine corrosion environment, was used in previous experiments under Contract N-00019-71-C-0119. It was described in the November 19, 1971, Summary Report. In all cases, the 440C shafts showed excellent results. The corrosion resistance observed was equal to the corrosion resistance of chromium-plated shafts. M50 tool steel shafts, evaluated for comparison, showed corrosion at the edge of contact with the bearings, which was similar to that observed in previous experiments. Apparently, the superior inherent corrosion resistance of 440C stainless steel prevented attack by seawater in the corrosion test. This capability is important for bearings being applied in aircraft that will be used near a marine environment.

The results of the performance experiments show that 440C stainless steel holds potential for a high-performance, corrosion-resistant shaft material for use with beryllium copper bearings. Although its elevated-temperature performance was inconsistent in terms of obtaining good compatibility, in all cases the wear rates were sufficiently low that the material, despite its inconsistencies, should be useful. No instances of catastrophic wear or failure were experienced.

AISI 4340 and 300-M Shafts

Experiments were conducted to evaluate the performance of hardened 4340 and 300-M shafts for use with beryllium-copper bearings. The shafts were hardened to R_c 52 and R_c 54, respectively, to achieve their maximum useful strength and hardness. While field applications

utilize chrome plating on these materials, initial experiments were run with unplated shafts to eliminate the variable of plating integrity. A bearing stress of 40,000 psi was used in all cases. Batch 2440 of MIL-G-81322 grease was supplied with a hand-operated grease gun at two-hour intervals. The results of the experiments are presented in Figures 6 and 7. In general, the performance of both shaft materials was excellent for all experimental conditions. The wear increased with increasing operating temperature, but was not excessive at 350 F (the maximum recommended temperature for MIL-G-81322 grease). These results also show that grease Batch 2440 provides adequate high-temperature lubrication. Comparing Figures 6 and 7 shows that the 4340 shafts provided slightly better bearing wear performance than did the 300-M shafts. One plated shaft of each type was also run for comparison. Both shafts performed well--wear was comparable to the unplated shafts at the same temperature.

Experiments were also conducted with the hardened shafts at the higher stress of 60,000 psi. The results with unplated shafts are presented in Figure 8. The bearing operated against the 4340 shaft showed a wear pattern typical of that found for bearings operating without distress--a plateau in wear after 20,000 cycles of operation. In contrast, the wear of the bearing operated against the 300-M shaft was linear, although the wear after 60,000 cycles was not excessive. Both shafts showed evidence of polishing and uniform, light transfer of beryllium copper with no roughening or signs of incipient failure.

Since AISI 4340 and 300-M shaft materials are usually chrome plated for corrosion protection, experiments were conducted at high stress levels using plated shafts to assess the effect of the plating. As already presented in Figures 6 and 7, two chrome-plated shafts operated satisfactorily at 300 F against beryllium-copper bearings. However, one chrome-plated 300-M shaft fractured from fatigue after 42,000 cycles operating against a beryllium-copper bearing at 350 F.

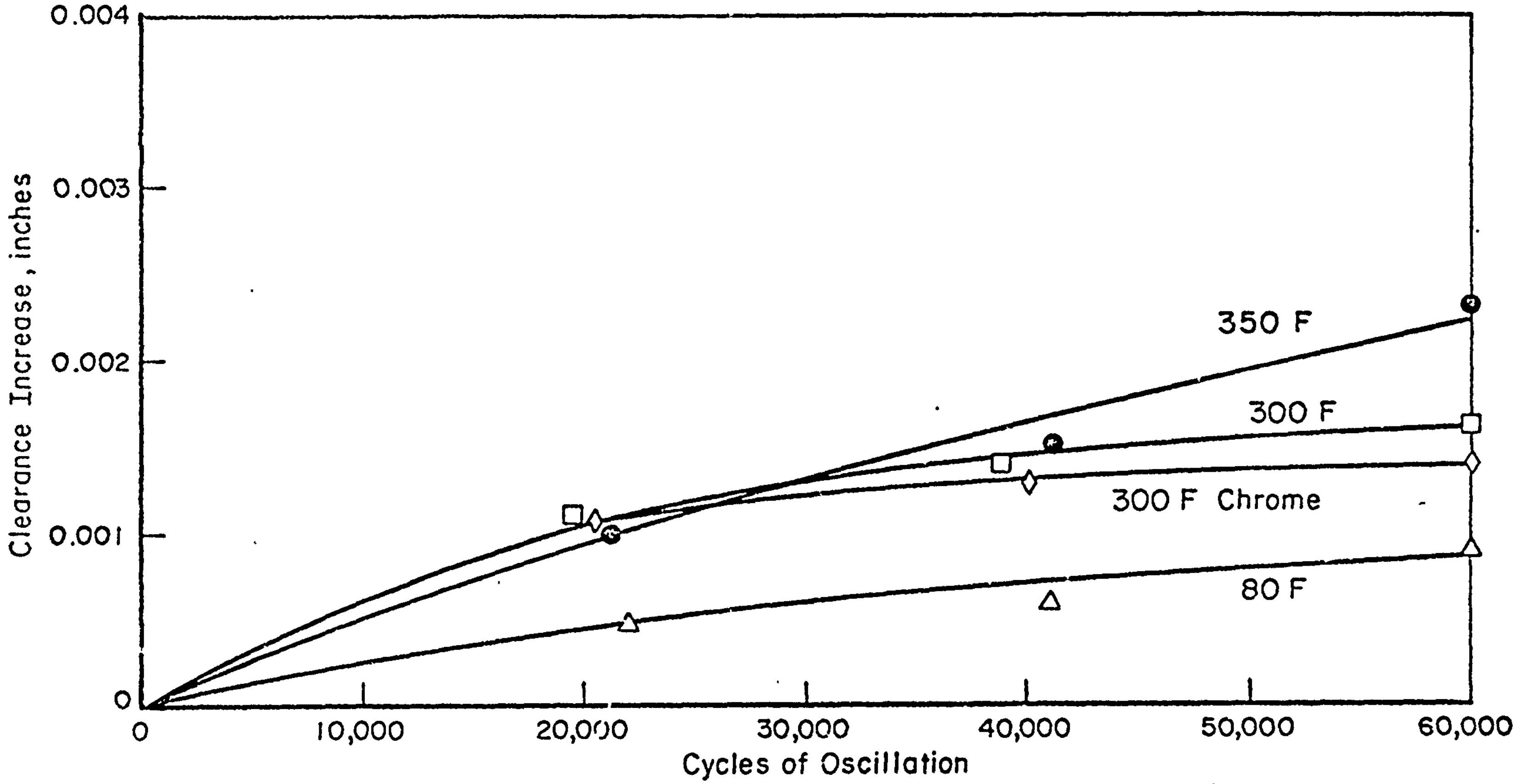


FIGURE 6. PERFORMANCE OF BERYLLIUM-COPPER BEARINGS AGAINST CHROME-PLATED AND UNPLATED 4340 SHAFTS

40,000 psi, Batch 2440 MIL-G-81322 Grease

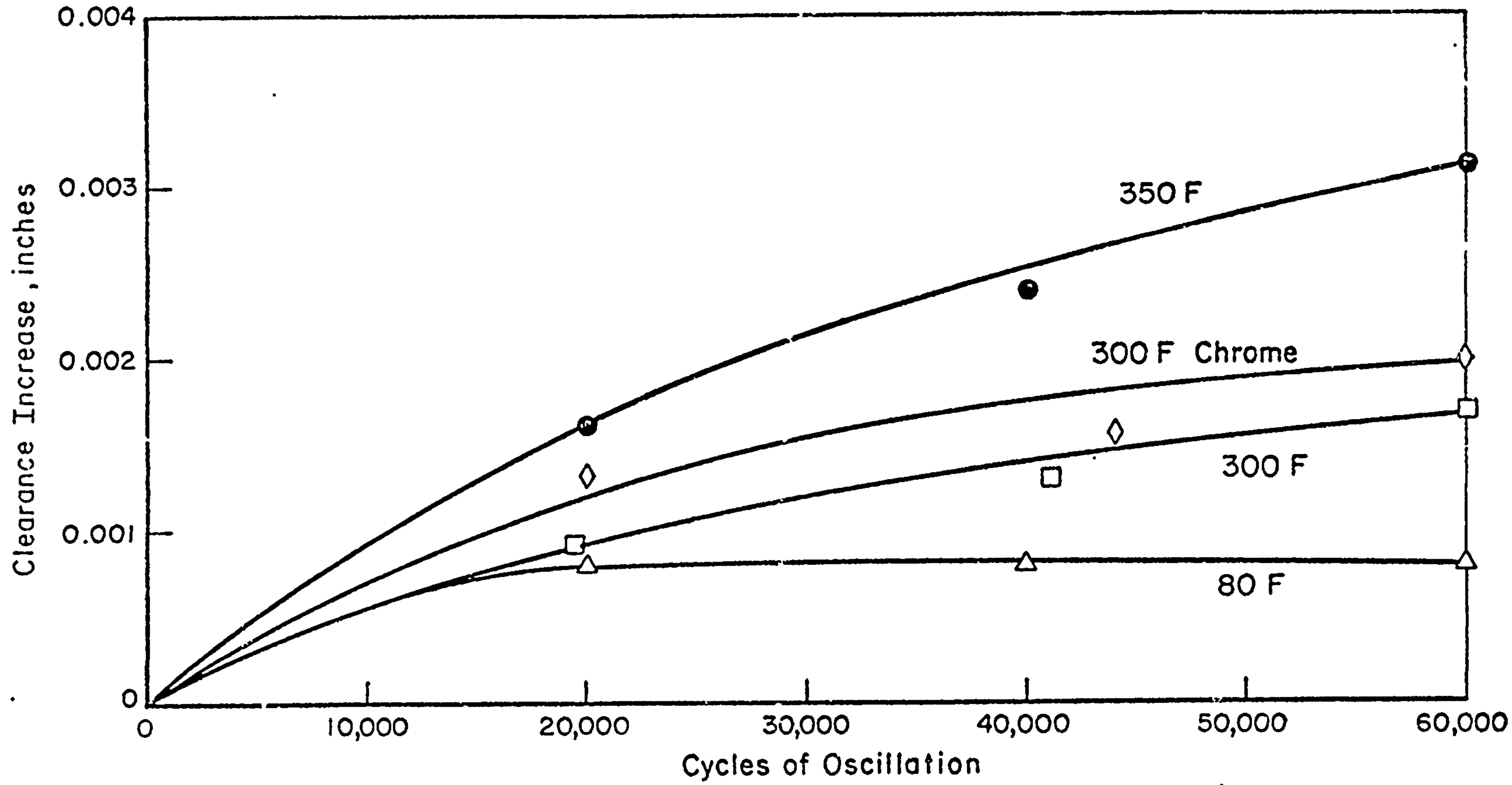


FIGURE 7. PERFORMANCE OF BERYLLIUM-COPPER BEARINGS AGAINST CHROME-PLATED AND UNPLATED 300-M SHAFTS

40,000 psi, Batch 2440 MIL-G-81322 Grease

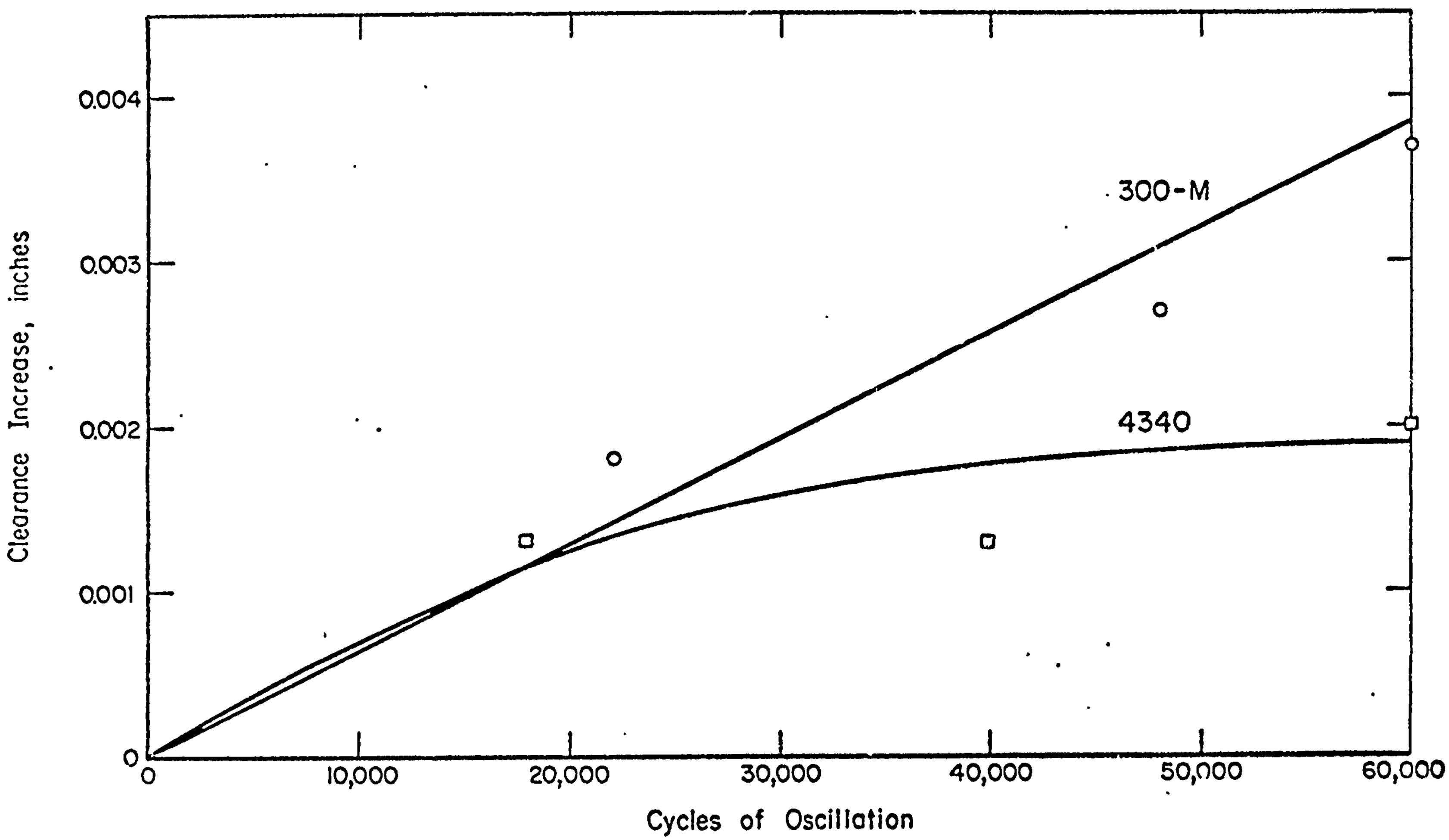


FIGURE 8. PERFORMANCE OF BERYLLIUM-COPPER BEARINGS AGAINST UNPLATED STEEL SHAFTS AT 60,000 psi

Batch 2440 MIL-G-81322 Grease, Ambient Temperature

When the operating stress was raised to 60,000 psi, all of the shafts fractured. The results are summarized in Table 1. All of the experiments were conducted at room temperature using MIL-G-81322 grease lubrication. While the inconsistent results obtained with chromium-plated shafts in previous experiments usually correlated with the tenacity of the bond between the chromium plating and the shaft, the bond was excellent on all four shafts in Table 1. Therefore, the fractures were not initiated by gross cracking or peeling of the chromium plating. Since hydrogen embrittlement is an inherent problem with chromium plating, two of the shafts were baked for 4 hours at 375 F prior to testing to effect a possible improvement. As seen in Table 1, no improvement resulted. However, for maximum improvement the baking should be performed immediately after plating.

TABLE 1. RESULTS WITH CHROMIUM-PLATED 4340 AND 300-M SHAFTS WITH BERYLLIUM-COPPER BEARINGS AT 60,000 psi

Shaft Material	Treatment After Plating	Cycles to Shaft Fracture	Bearing Wear at Fracture, in.
4340	None	19,500	0.0001
4340	Baked	42,000	0.0007
300-M	None	17,850	0.0000
300-M	Baked	20,300	0.0003

In an attempt to provide maximum fatigue resistance, hardened AISI 4340 and 300-M were shot peened prior to plating and baked immediately after plating. The shot peening conformed to procedures in MIL-S-13165B. using a S-110 shot size at an intensity of 6-10 A. After chrome plating, the surfaces measured 51 μin. cla in roughness, which was much higher than were the values (approximately 9 μin. cla) measured after normal grinding and plating. Therefore, the shafts were polished with abrasive paper after plating to obtain a roughness of 9 μin. cla.

The results with the shafts run at 60,000 psi were excellent. Both the chrome-plated AISI 4340 and 300-M shafts operated successfully without fatigue, and the measured wear was less than 0.002 inch (see Figure 10). These limited results show that chrome-plated shafts can be operated at high stress levels without fatigue--provided proper steps are taken to minimize the initiation of fatigue cracks.

The experiments with hardened AISI 4340 and 300-M shafts have shown that satisfactory bearing performance can be obtained with both materials. Although 300-M is used at a slightly higher hardness than is AISI 4340, no indication of improved performance resulting from the increased hardness (and associated strength) was noted in the experiments. Excellent results were obtained with unplated shafts. Therefore, it must be concluded that the benefit of hard chrome plating in this application is limited to corrosion protection and not enhancement of wear resistance. Conventional chrome plating without precautions against embrittlement made the shafts prone to failure by fatigue cracking when operated at high bearing stress levels. Limited experiments with shafts treated to minimize fatigue as a result of plating were successful. Therefore, any chrome-plated shafts operating at high stress levels should be shot peened and baked to minimize failure by fatigue.

Grease and Additive Evaluations

MIL-G-81322 Greases

Experiments conducted in recent programs under Contracts N-00019-70-C-0282 and N-00019-71-C-0119 identified performance differences at elevated temperatures among various greases meeting the MIL-G-81322 specification. For some qualified products, reliable performance in airframe bearings was limited to temperatures below 300 F, even though the maximum temperature of operation for MIL-G-81322 greases is specified to be 350 F. No correlation in degradation of elevated-temperature performance could be obtained when attempts were made to assess the

deficiencies using other grease-evaluation techniques, such as determining its wear-prevention capabilities in a 4-ball E.P. tester.

The three versions of MIL-G-81322 evaluated in the current program showed no performance deterioration at elevated temperatures. Although slight performance differences are suggested by comparing Figures 4, 5, 6, 7, and 8, all of the greases provided satisfactory lubrication regardless of temperature. Apparently, formulation modifications have been made in the recent MIL-G-81322 greases that permit adequate elevated-temperature lubrication of airframe bearings.

Additive Evaluations

Experiments were conducted to determine whether additions of ATA improve the performance of a MIL-G-81322 grease. An addition of 5 percent ATA was made at BCL, and this formulation was compared with unmodified MIL-G-81322 and with the identical grease containing 5 percent MoS_2. Aluminum-bronze bearings were chosed for the experiments; they were operated at 30,000 psi (normally an excessively high stress for this material). M50 tool steel shafts were used at ambient temperatures.

The results of the initial experiments are presented in Figure 9. The additions of either ATA or MoS_2 reduced the bearing wear slightly from that measured for the bearing lubricated with unmodified grease. However, since the bearing lubricated with the unmodified grease wore less than only 0.0015 inch after 60,000 cycles, the improvement is not highly significant. More important was the improved friction performance resulting from the ATA addition. While the bearing lubricated with the unmodified MIL-G-81322 grease maintained a coefficient of friction between 0.04 and 0.08, the bearing lubricated with MIL-G-81322 grease containing 5 percent ATA showed a coefficient of friction between 0.01 and 0.04, with brief excursions to 0.06. The MoS_2 addition also improved the friction performance; this bearing had a coefficient of friction between 0.02 and 0.06. These initial results indicate that

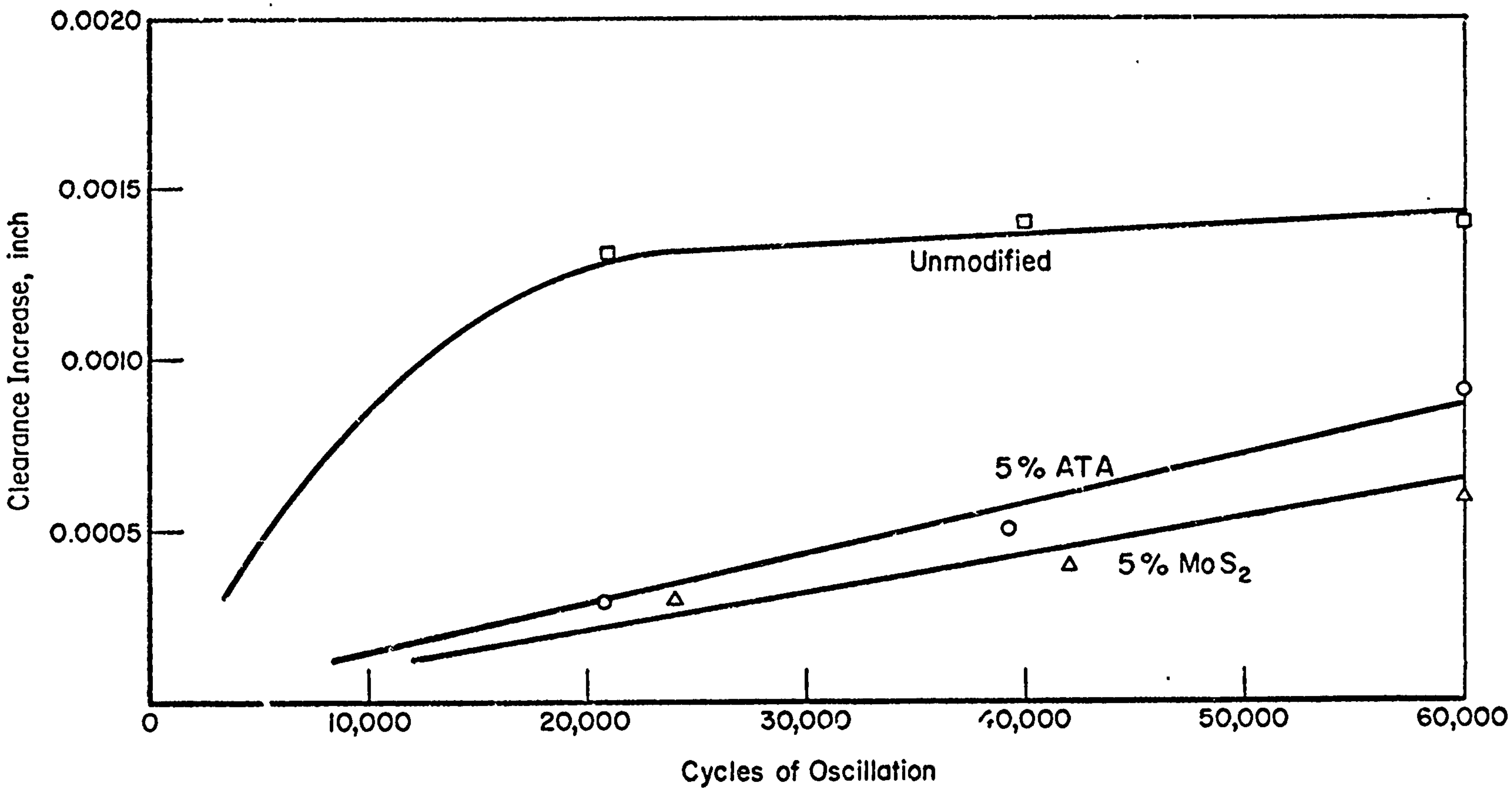


FIGURE 9. EFFECT OF ADDITIVES TO MIL-G-81322 GREASE ON PERFORMANCE OF ALUMINUM-BRONZE BEARINGS

M50 Shafts - 30,000 psi - Ambient Temperature

additions of ATA to MIL-G-81322 grease can lower the coefficient of friction and effect a slight improvement in wear performance. MoS_2 additions appear to have a similar effect to a lesser degree.

Experiments were also conducted using modified greases to lubricate aluminum-bronze bearings operated against shot-peened chrome-plated shafts (described earlier) at very high stress levels. The results are presented in Figure 10. It had been determined previously that aluminum-bronze bearings with conventional hard chrome platings were limited to operation at stresses below approximately 20,000 psi. Operation at stresses above 20,000 psi could be obtained only by using beryllium-copper or tool-steel bearings. The current results show that satisfactory performance is possible at stresses of 60,000 psi. Two factors contributed to the increase in performance shown in Figures 9 and 10 for aluminum-bronze bearings. First, the addition of 5 percent ATA or of 5 percent MoS_2 is significant. Figure 10 shows that at 60,000 psi the results are similar to those at the 30,000 psi stress levels shown in Figure 9, i.e., the bearings lubricated with greases containing the additives showed lower wear. Second, the shot-peened chrome-plated shafts performed well throughout the experiments. Previously, poor adhesion of the chrome plating caused accelerated wear at high stress levels and led to catastrophic wear at stresses of 30,000 psi and above. The excellent adhesion of chrome and the excellent fatigue resistance of these shafts were primarily responsible for the satisfactory performance.

Plasma-Sprayed Bearing Coatings

A brief evaluation was made of the suitability of plasma-sprayed coatings for airframe-bearing applications. Previous experiments conducted under Contract N 00019-71-C-0119 showed a potentially superior performance for plasma-sprayed aluminum-bronze coatings when compared with that for the conventional cast material. The plasma-spray technique has

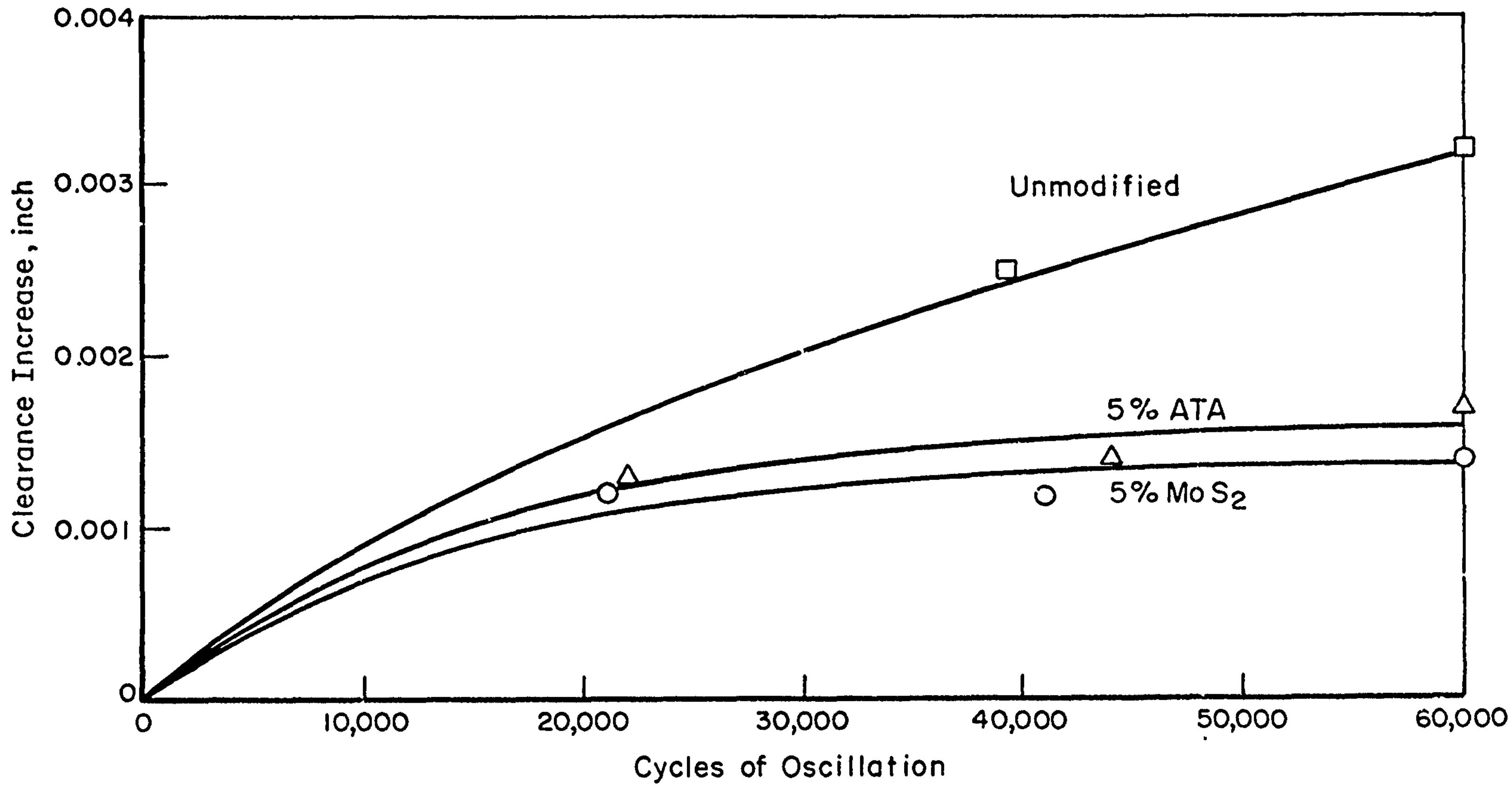


FIGURE 10. EFFECT OF ADDITIVES TO MIL-G-81322 GREASE ON PERFORMANCE OF ALUMINUM-BRONZE BEARINGS AT VERY HIGH STRESSES

Shot-Peened Chrome-Plated 4340 Shafts - 60,000 psi - Ambient Temperature

a great potential for weight savings. Therefore, spraying new bearings in place on an airframe or using the technique for repair of used bearings deserves further efforts to develop the process for practical applications.

Three experiments were performed in the current program to compare the performance of three different experimental materials. A 0.010-inch layer of the materials was deposited on the inside diameter of oversized bearings. The bearings were then machined to size for evaluation in the normal manner. The results are presented in Table 2.

TABLE 2. PERFORMANCE OF THREE EXPERIMENTAL PLASMA-SPRAYED AIRFRAME-BEARING MATERIALS

MIL-G-81322 Grease Lubrication, M-50 Shafts, 40,000 psi, Ambient Temperature

Bearing	Alloy	Base Material	Cycles	Wear, in.	Comments
LCU-3, S392-167-6	Beryllium Copper 25	Beryllium Copper	60,000	0.0026	Excellent performance
LAL-X, S392-165	Aluminum	Aluminum	13,000	0.10	Run terminated; excessive wear
LCU-Y, S392-166	Aluminum Bronze	Aluminum Bronze	20,000	--	Shaft fractured, coating peeled off

The plasma-sprayed beryllium-copper bearing showed encouraging results which warrant further investigation. The coating remained intact throughout the experiment and there was no evidence of cracking or edge chipping. The wear was slightly higher than that normally experienced

with conventional beryllium copper under the same conditions; however, it was acceptable. The broken shaft destroyed the aluminum-bronze bearing, and the applied stress exceeded the capabilities of the aluminum bearing.

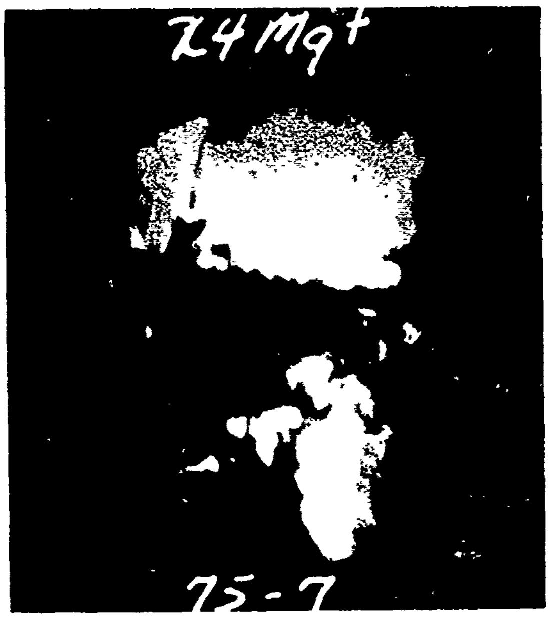
Bearing-Film Analysis

Ion Microanalyzer

Throughout the course of the airframe-bearing experiments, a correlation has been observed between degraded bearing performance and the presence of a blue, purple, or brown film on the load-carrying surface of the bearing. Bearings exhibiting excellent performance in terms of low wear and low friction typically have polished load-carrying surfaces, which are free of visible films. A beryllium-copper bearing showing "poor" performance and one showing "good" performance (no visible film) were studied using an ion microanalyzer in an attempt to determine whether the composition of the surfaces could be related to the reduced bearing performance.

Surprisingly, a film of similar composition was found on the surfaces of both bearings. The only apparent difference was that the film on the bearing showing reduced performance was thicker, which made it more visible. A light micrograph of a typical area containing the surface film is shown in Figure 11a. A micrograph of the same area in a scan for magnesium is shown in Figure 11b, which demonstrates the image obtained from a particular scan. The magnesium concentrations show up as white areas of high emission. Similar strong images were obtained for beryllium, aluminum, silicon, calcium, copper, sodium, chlorine, iron, potassium, manganese, and chromium. Weaker images (indicating a much lower concentration) were obtained for lithium, fluorine, carbon, and vanadium. Cobalt, which is present in beryllium copper as an alloy addition, was completely absent from the film, while beryllium and copper produced strong images. An optical-emission-spectroscopy analysis was performed on a grease sample to determine

a. Light Micrograph of Film



b. Scan for Magnesium

(The White Areas Delineate Magnesium Concentration)

FIGURE 11. FILM ON BERYLLIUM-COPPER BEARING SURFACE
STUDIED WITH ION MICROANALYZER

the concentration of metallic elements contained in the grease for comparison with those found in the film. The results are presented in Table 3. All of the metallic elements found in significant concentration in the films (and not originating in the bearing material) were present in the grease, which was their likely source. The chlorine, which is not detectable by optical emission spectroscopy, may have originated in an E.P. additive. Since the only significant difference found between the films on a satisfactory and distressed bearing surface was the thickness, a film comprised of a number of metallic elements is probably present at all times. The operation of the bearing in periods of higher wear and friction probably induces increases in film thickness. This may be the result of higher local temperatures caused by the higher input of frictional energy at the surfaces. It is presumed that the film is formed intermittently during the wear process and does not provide continuous boundary lubrication. Since the thicker film was associated with higher wear, the wear process might be chemical in nature.

TABLE 3. OPTICAL EMISSION SPECTROGRAPHIC ANALYSIS OF MIL-G-81322 GREASE SAMPLE

Metallic Element	Concentration in Grease, percent
Al	0.4 - 0.8
Si	1.0 - 2.0
Ca	0.5 - 1.5
Mg	0.2
Na	0.2 - 0.4
Fe	0.2
Pb	0.002
Ti	0.004
Cu	0.001
Mo	0.0004
B	0.0004
Mn	0.0004
Ni	0.0001
Zr	0.0008
K	0.04
Cr	0.0001
Accuracy:	±50 percent or better

<u>Ion Scattering Spectrometer</u>

A surface analysis was also performed on a worn bearing using an Ion Scattering Spectrometer (ISS). An aluminum-bronze bearing, subjected to sliding contact under 30,000 psi bearing stress in the airframe bearing simulation apparatus, was cut in half and examined by optical microscopy. The contact zone appeared to be burnished; the surface was partly copper in color and partly blue-to-purple in color. Some very fine scratch marks were found in the burnished zone. A piece was cut out of the burnished zone and subjected to analysis using an ISS.

The ISS is a relatively new surface analytical tool with which it is possible to determine elemental composition of surfaces with a 20 A resolution. The device provides a true analysis of the outer 20 A of a surface. The analysis is performed by impinging a beam of ions on the surface to be analyzed. The reflected ions are collected and their energy change is measured, the energy change being a function of the atomic weight of the reflecting surface atoms. The ion beam also slowly removes atoms by a sputtering process so that a surface layer is removed gradually and its composition can be determined as a function of depth. Depth of surface removal has a practical limit of 10,000 A ($\sim 50 \times 10^{-6}$ in.).

The results of the analysis are summarized in Figures 12 and 13, reproductions of spectrograms. Figure 12 shows a spectrogram made in the burnished area and represents composition of a surface layer 10 A deep. The significant peaks are labled. This spectrogram shows that not only are there present elements associated with the lubricant (Na, Ca, K), but also copper and aluminum from the alloy. A significant oxygen peak is present also. The chart shown in Figure 13 shows the composition of the same area at a 5000 A depth ($\sim$ 20 microinches). This spectrogram shows a significant decrease in Na, Ca, and K and an increase in copper and aluminum content. In addition, the ratio of oxygen to aluminum and copper has been reduced.

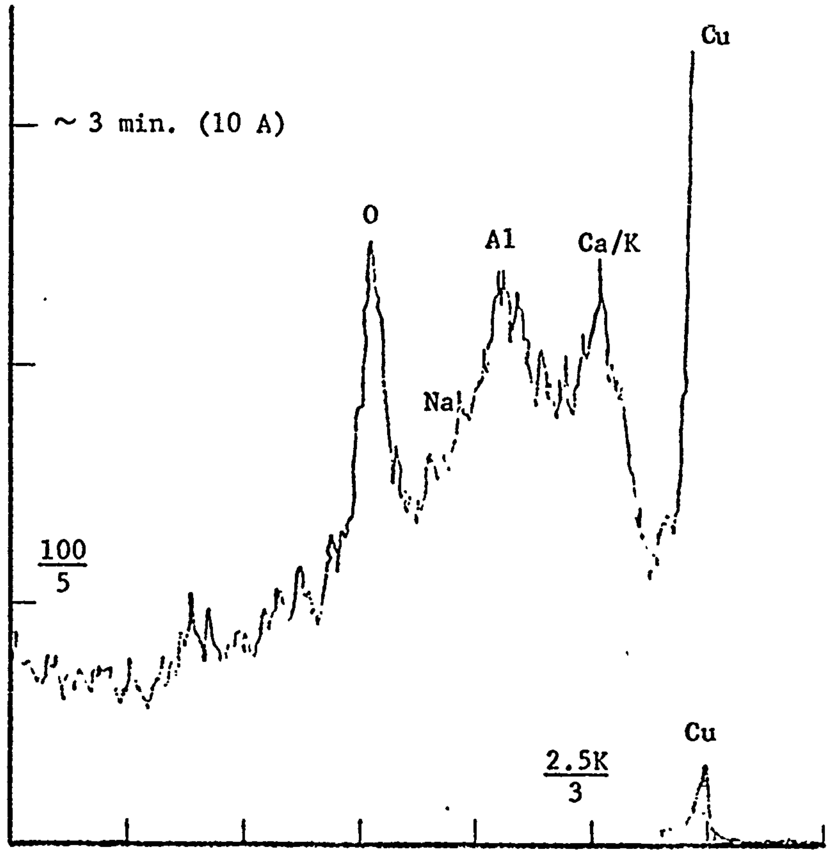


FIGURE 12. ISS SPECTROGRAM OF WORN ALUMINUM BRONZE SURFACE AT 10 A DEPTH

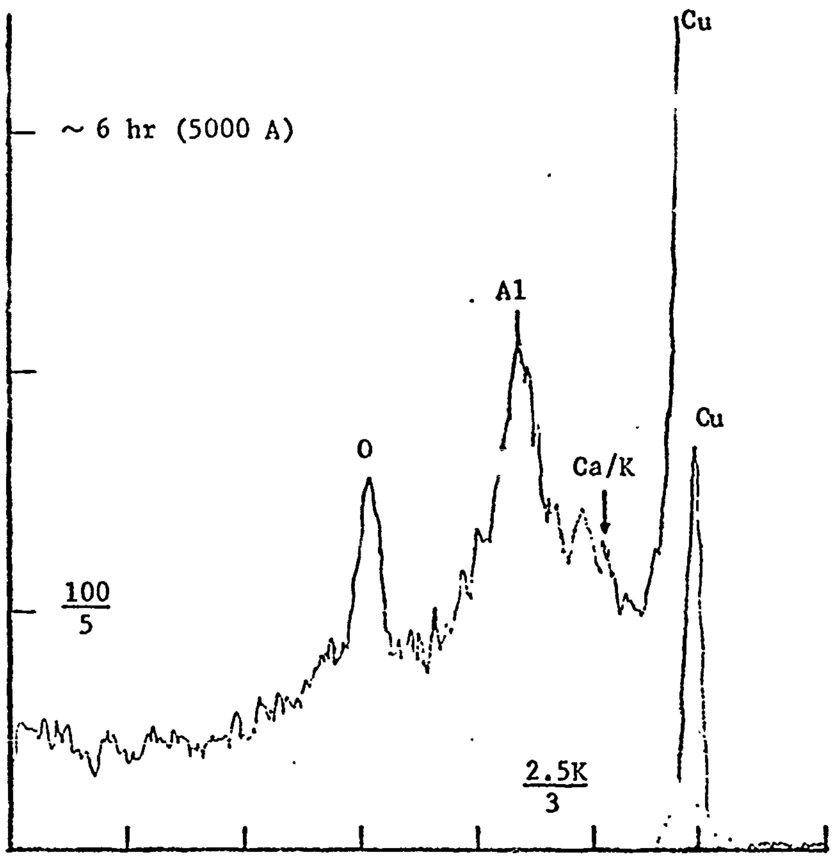


FIGURE 13. ISS SPECTROGRAM OF WORN ALUMINUM BRONZE SURFACE AT 5000 A DEPTH

The above results indicate that the burnished area is composed of a complex metal-organic film approximately 20 to 30 microinches thick. Since it contains elements from both the lubricant and the bearing materials, the film is presumably a surface-reaction product. Boundary lubrication is accomplished by surface chemical action and the resulting boundary films are tough, well bonded, and very thin. Oxidation of the aluminum in the aluminum bronze is also indicated as a possible factor in the film formation.

In addition to the findings described above, the analysis showed that the bearing surface was enriched in aluminum. Presumably, the aluminum enrichment is the result of diffusion of aluminum to the worked surface layers (heavily dislocated region) during bearing operation. This may also occur during surface finishing of the bearing. The aluminum enrichment of the surface is of significance to the boundary-lubrication process--especially since one mechanism of boundary lubrication with the materials involved assumes that surface chemical reactions take place.

Boundary-lubrication experiments involving binary copper alloys that have been carried out by Matveevsky*, showed that for a copper-aluminum alloy lubrication effectiveness was a function of aluminum content. At about 6-percent aluminum, boundary lubrication was the least effective, while at 10 percent aluminum content the most effective boundary lubrication resulted. This sensitivity to composition suggests that strain-induced alterations in surface composition may be significant factors in the boundary-lubrication process. Thus, the bulk composition of the bearing material may not reflect the actual surface chemistry involved in the lubrication process. Furthermore, change in aluminum content in surface layers of the aluminum bronze can result in phase changes. The 7 percent aluminum-bronze used in the Battelle bearing evaluations is an α solid solution, one-phase material. Above 7 percent aluminum, a second harder phase (β) will occur if the alloy is quenched from high temperature.

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* R. M. Matveevsky and O. V. Lozovskaya, "The Influence of Alloying on the Antifriction Properties of Binary Alloys Under Boundary Lubrication Conditions", Wear, v. 11, 1968, pp 69-75.

Such a phase change might be possible in heavily loaded aluminum-bronze bearings where the combined effect of localized frictional heating and plastic deformation would develop a new phase in the surface structure of the alloy. Presumably such a phase change would alter mechanical properties of the surface.

The above considerations are of importance when dealing with improving methods for selection of lubricants for heavily loaded plain bearings operating under boundary conditions.